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STUDY TO ESTABLISH TRANSIENT SUPPRESSION TECHNIQUES AND CRITERIA

by

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PHASE I REPORT - LITERATURE SEARCH

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Abstract

20104

This is a report on the literature study phase of a contract to establish methods of minimizing electrical interference from switching inductive circuits. The bibliography lists the articles reviewed. The report contains a summary of the pertinent material found. Author

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CHAPTER I

INTRODUCTION

The presence of arcing and high voltage transients at the contacts of switches which energize inductive devices is well known. In certain cases these transients interfere with the normal operation of the circuit or neighboring circuits through conduction or radiation. For this reason a great deal of effort has gone into the design and development of special arc-suppressing networks.

Several of the more common types of suppression circuits described in the literature utilize resistors, capacitors, diodes, and varistors placed either across the contacts of the switch or in parallel with the inductive load.

The study presently underway concerns the investigation and evaluation of transient suppression techniques. This report describes the results of work on the literature search portion (Phase I) of the contract. It consists primarily of a summary of the important material found in the literature and a bibliography of these and other references.

CHAPTER II

EQUIVALENT CIRCUITS FOR INDUCTIVELY LOADED SWITCHES

This chapter contains a description of the transient waveform beginning with the ideal model of an inductively loaded switch and proceeding to more realistic models. This approach is used in order to clarify the understanding of the problem involved in the practical application of arc-suppression techniques discussed in Chapter III.

2.1 Ideal Inductor - Ideal Switch

According to basic circuit theory the voltage across an ideal inductor is equal to some constant (the inductance) times the time rate of change (the time derivative) of the current. This may be expressed in equation form by (see Ref. 1, for instance)

$$V_L = L \frac{di}{dt}$$

where V_L = voltage across the inductor

L = inductance

i = instantaneous current throughout the inductor

$\frac{d}{dt}$ = derivative with respect to time.

Thus, when the current through an inductor is instantaneously interrupted, theory predicts that the potential across the inductor must go to infinity.

2.2 Ideal Inductor - Realistic Switch

Physically the potential will never approach infinity since at some point in the circuit the high potential will cause a breakdown or arc serving as a current path allowing the current to decay at a finite rate and thus limit the potential buildup. In almost all cases this breakdown will occur at the contact points since it is here that a very small separation of surfaces and low dielectric strength yields the highest electric fields.

The energy which sustains arcing at the contacts is that which is stored in the magnetic field of the inductor, and its ideal magnitude is given by the relation[1,2]

$$W = 1/2\ LI^2$$

where W is the stored work or energy

L is the inductance value

I is the current through the inductor before contact is broken.

If the arcing is not suppressed, most of the stored energy is dissipated as heat at the contacts.

2.3 Realistic Inductor - Ideal Switch

It is recognized of course, that each inductor will have a certain amount of capacitance and resistance which generates a transient waveform somewhat different from that of the pure impulse discussed above.

A simple model circuit that is useful in analyzing this waveform is shown in Figure 1, where L is the inductance, R_c is the resistance of the coil windings, C_c represents the effect of the turn to turn capacitance of the windings and C_L is the distributed lead capacitance.[3]

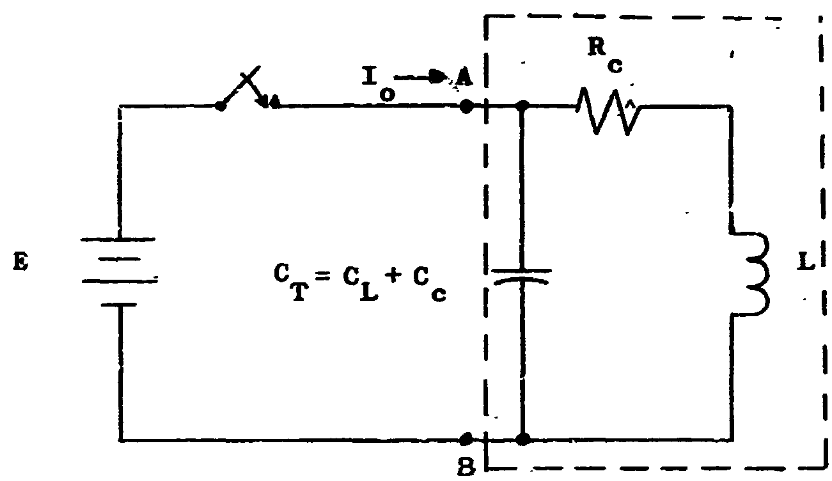


Figure 1. Equivalent Circuit of an Inductor

Referring to Figure 1, when the switch is opened the current I_o is interrupted. The current in the RLC loop continues to flow, however, due to the collapsing magnetic field of the inductor and charges the capacitor. Recalling that the voltage across C_T is given by

$$V_{C_T} = \frac{1}{C_T}\int_0^t i(t)dt$$

the initial charge rate of the capacitor is[4]

$$\text{charge rate} = \frac{dV_{C_T}}{dt} = \frac{I_o}{C_T}$$

since the current through C_T at $t=0_+$ is the steady state current I_o. If the capacitance is small, as it usually is, C_T will charge up rapidly. In the simplest form the voltage across terminals A-B would rise to a peak value and then decrease as an overdamped, oscillatory or critically damped sinusoid depending on the values of R_c, L, and C_T as shown in Figure 2[5].

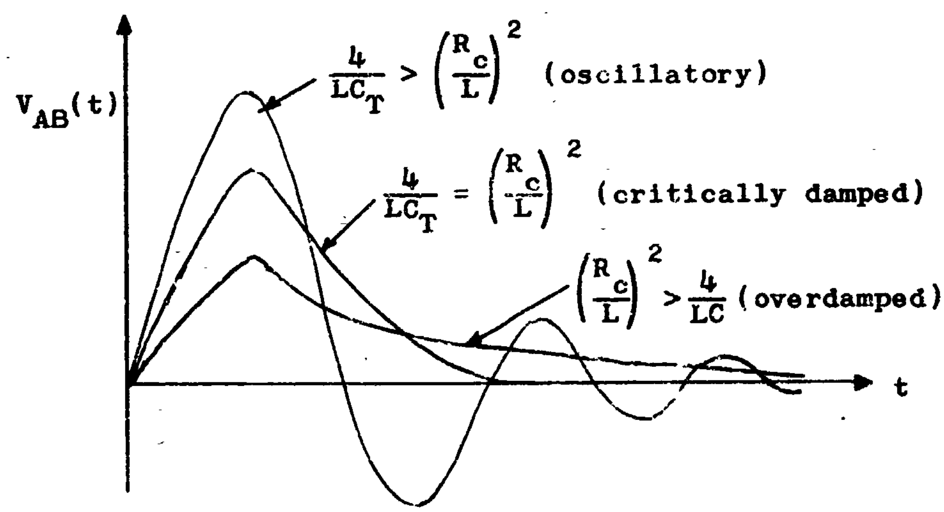


Figure 2. RLC Transient Voltage Curves

In most cases, since C_T and R_c are small the waveform will be an oscillatory damped sinusoid.

The voltage and current waveform upon closure of the switch are considerably different from those generated during opening. In this case the voltage across the terminals A-B of Figure 1 is a step function as shown in Figure 3. This is a transient, of course, and a Fourier analysis would show that it contains a continuous spectrum of frequencies which can radiate or be coupled into other circuits as noise.

The current, however, is initially short circuited by the shunt capacitance C_T causing an infinite current spike from which it recovers and dies out as a damped sinusoid as shown in Figure 4. In an actual circuit this spike is limited by lead resistance and inductance that are neglected in the elementary model circuit.[6]

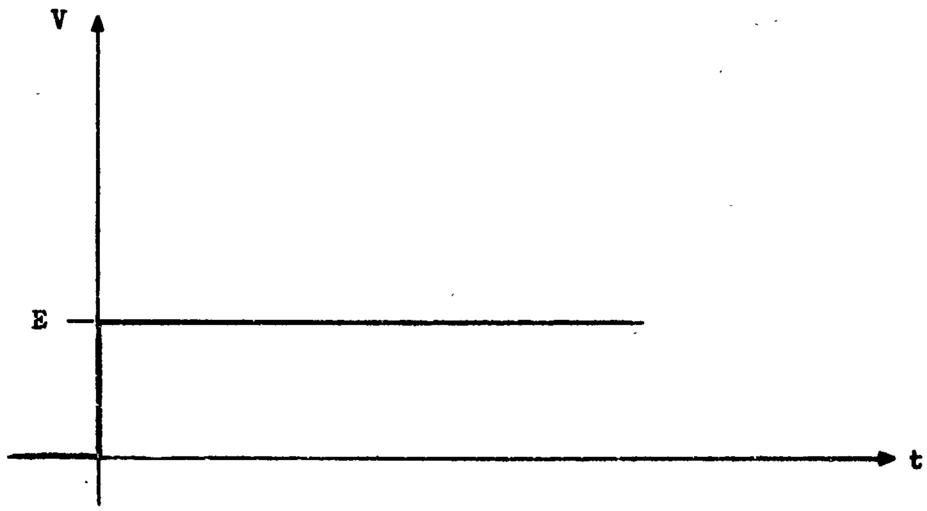


Figure 3. Voltage Curve Across Inductor at Switch Closure

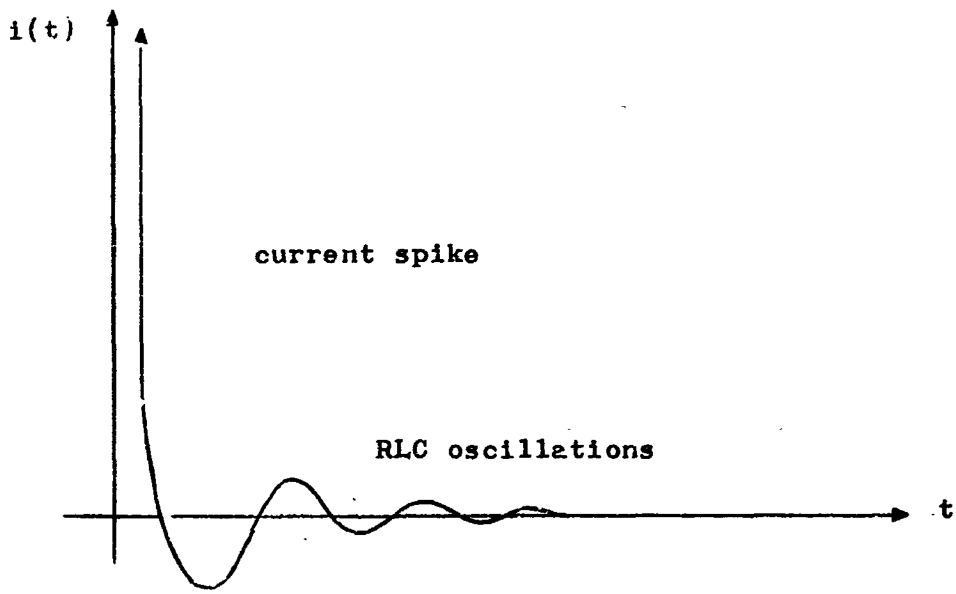


Figure 4. Current Response Curve Upon Switch Closure

The circuit shown in Figure 1, is perhaps, the simplest non-trival model of an inductor and switch which has response characteristics similar to those of the physical circuit. By increasing the complexity of the model to take into account such things as lead inductance, lead resistance and leakage inductance of the coil, a better approximation of the physical circuit can be obtained. For example, the circuit of Figure 5 is proposed by Gumley[4]. Of course, with the addition of transient suppression components into the circuit, the model becomes more complex, and thus more difficult to analyze.

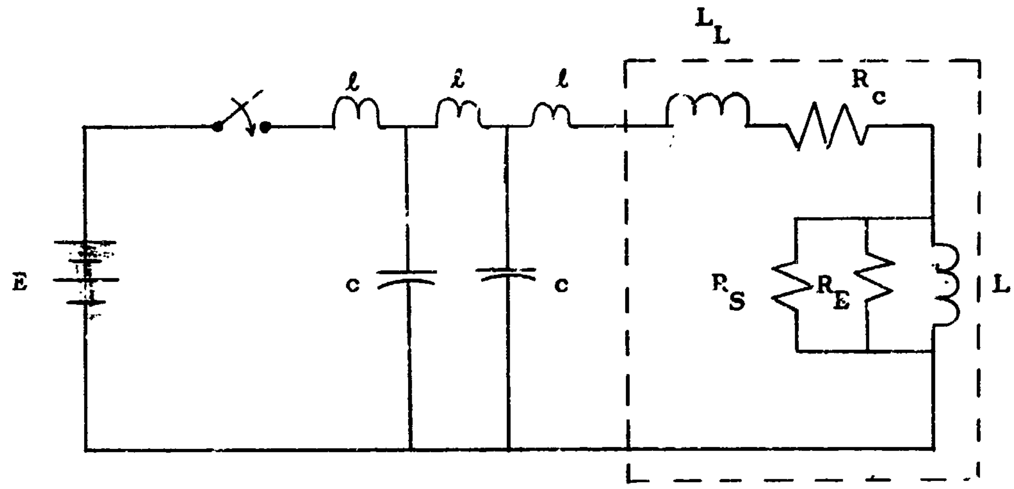


Figure 5. Gumley Model of Inductor in Circuit

L = coil inductance

c = distributed lead capacitance

ℓ = distributed lead inductance

L_L = leakage inductance of coil

R_c = coil resistance

R_E represents eddy current losses in coil

R_S represents presence of copper sleeve

2.4 Realistic Inductor - Realistic Switch

Experimental results show that the characteristic transient waveform across the inductive load of an opening switch contains:

1. a region of showering
2. RLC oscillations

as shown in Figure 6.[2,4]

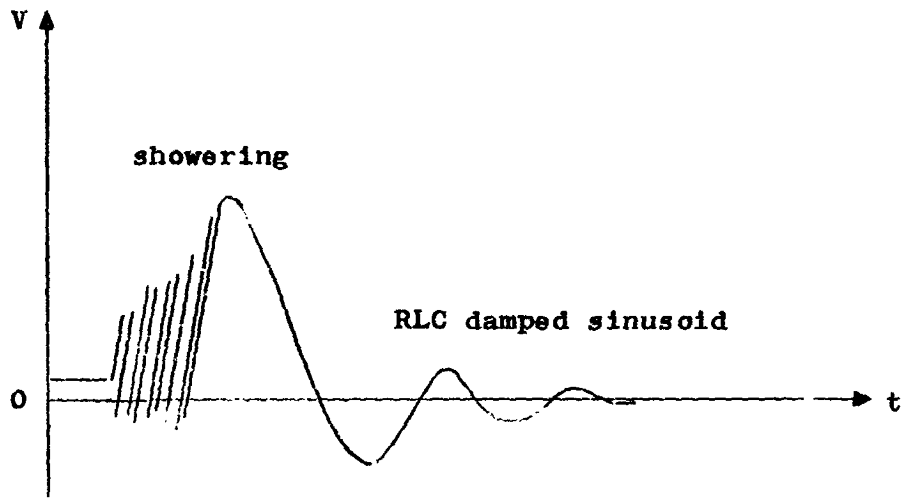


Figure 6. Transient Waveform Across Inductor-Switch Opening

This waveform may be explained by the fact that the potential across the inductor also appears across the contacts of the switch, and an arc is formed at the contacts when this capacity potential equals the minimum breakdown voltage of the media between the contacts (approximately 300 volts for air). The capacitor then discharges through the electrical conduction path provided by the arc and, in turn, reduces the potential to a point where the arc extinguishes. This process occurs repeatedly producing the sawtooth waveform called showering until the energy in the circuit is sufficiently dissipated through R so that an arc can no longer be formed. The remaining energy then dies out in a damped sinusoidal manner.

Since in many cases complete elimination of noise using suppression techniques is not required, or possibly can be achieved more satisfactorily by trial and error, many of the equivalent circuits found in the literature are of the simplest types.

CHAPTER III

SUPPRESSION TECHNIQUES

As discussed earlier, the problem of arc and transient suppression is one which deals with the dissipation of the energy stored in the inductive load. In general this dissipation takes place in some resistive component. This component may be the resistance inherent in the inductor itself or some external resistance which is in a current loop with the inductor.

Consider again the three parameter equivalent circuit of an inductor shown in Figure 7.

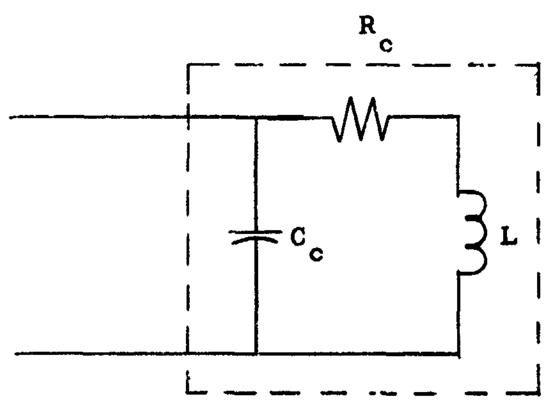
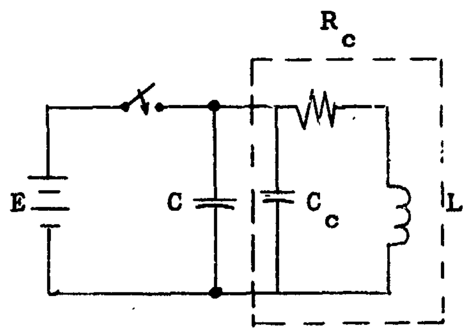


Figure 7. Inductor Equivalent Circuit

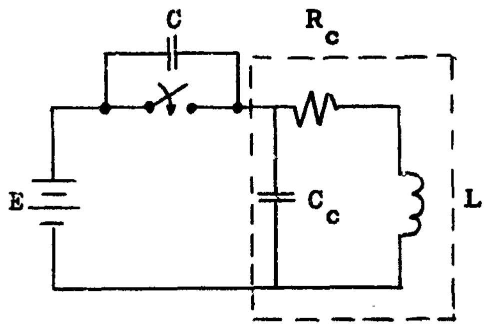
One observes that there is, according to this model, an internal loop which is able to dissipate some of the energy stored within the inductor. In most cases, however, the resistance and capacitance is too small to support and dissipate the energy fast enough to prevent high voltage buildup. Thus, external circuits must be used to aid in the suppression. The detailed analysis of the suppression networks will be included in the next phase report and at this time only a brief outline of some typical types of suppression will be discussed.

3.1 Capacitive Arc-Suppression

Possibly the simplest type of suppression network is that of the shunt capacitor.[7] The capacitor may be used either across the points or solenoid. Figure 8 shows a diagram of the capacitor suppression circuit. In circuit 8a , when the



a. Across Coil



b. Across Switch

Figure 8. Capacitor Suppression

switch is opened, the capacitor which is charged to a potential E will sustain the current flow through the inductor so that no discontinuity will occur in the current immediately upon opening. However, the inductor-capacitor will form a tank circuit and will oscillate. In circuit 8b, when the switch is opened the capacitor will begin to charge and again will permit current to continuously flow through the inductor, and again RLC oscillations will occur. In both of these cases the capacitor must be large enough so that the time constant of the circuit is of sufficient length to prevent the time rate of change of current in the inductor to remain small, thus preventing high voltage from being induced across the solenoid. For large solenoids which have low DC resistance, this capacitor will often be prohibitively large. Also, upon closure of both the circuits, the capacitor will be either charged or discharged through the switch with little resistance to limit the current. Thus, arcing may occur upon closure of the switch. Therefore, the use of purely capacitive shunts seems unrealistic for most purposes.

3.2 Resistor - Capacitor Suppression

One of the solutions to the problem of large capacitance and arcing upon closure is that of placing a resistor in series with the capacitor. In general, this limits the flow of current upon switch closure and also adds a dissipative element into the RLC network. The circuit shown in Figure 9[8,9] depicts the typical RC suppression network. Demayer[10], using the works of Holm[11], states that the potential across the switch of the circuit depicted in Figure 9 is given by

$$V = E + \frac{IR}{\omega}\left[\frac{1}{CR} - R_c\right]e^{-\alpha t}\sin(\omega t-\varphi)$$

where E = the power supply voltage

I = the circuit current before opening

R = the suppression resistance

C = the suppression capacitance

R_c = the solenoid resistance

L = the solenoid inductance

$\alpha = \frac{R+R_c}{2L}$ = damping coefficient

$$\omega_o = \frac{1}{\sqrt{LC}}$$

$$\omega = \sqrt{\omega_o^2 - \alpha^2}$$

$$\varphi = \text{arc sin}\,\frac{\omega LR_c(R-R_c)}{L-CR}$$

This equation is shown graphically in Figure 10. The peak voltage is given by the approximate relation

$$V_{max} \doteq E\left[1+\frac{L-CRR_c}{R_cLC}\,e^{-\alpha t_m}\right]$$

where

$$t_m \doteq \frac{1}{\omega}\left[\frac{\pi}{2} - \frac{\alpha}{\omega} + \frac{R_c-R}{LC}\right]$$

Demayer also points out that the voltage across the points is the same for either the switch or the solenoid when shunted.

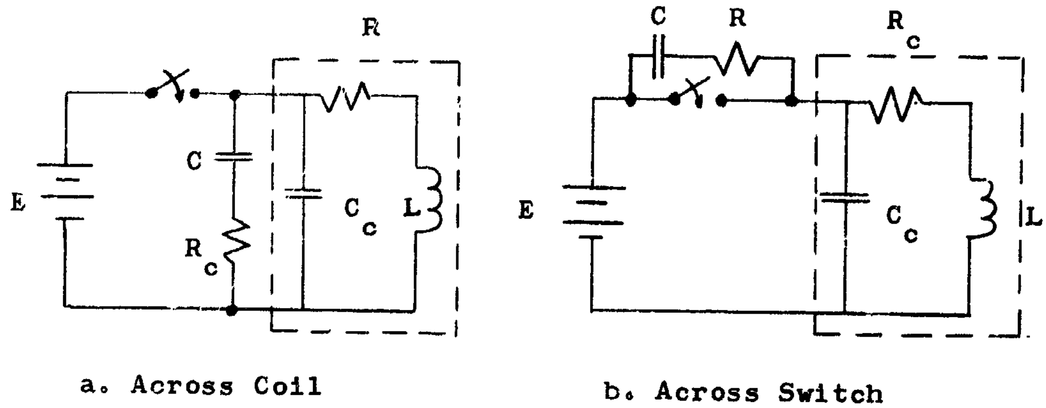


Figure 9. RC Suppression Networks

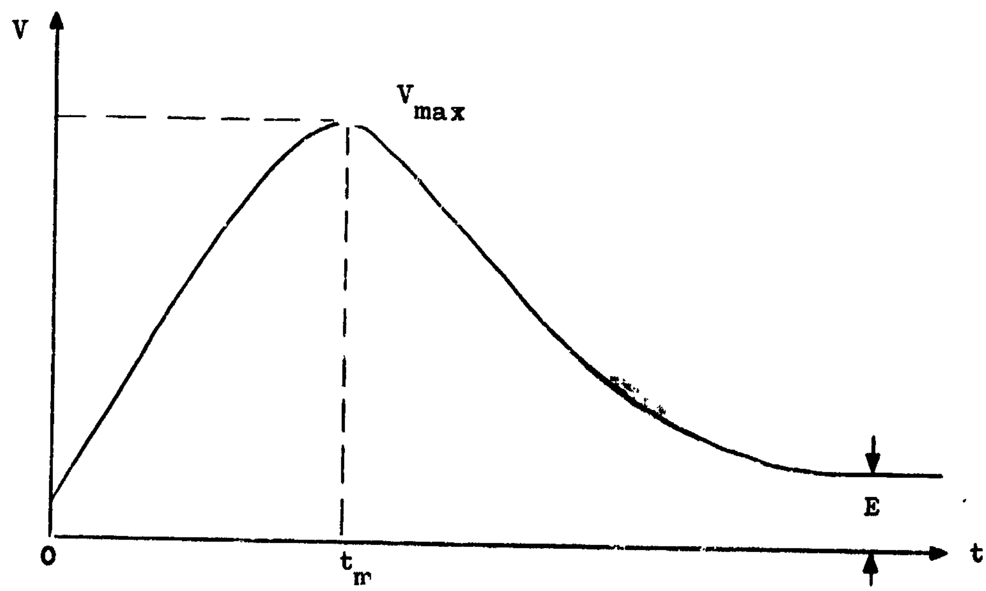


Figure 10. Voltage Response Curve for RC Suppression (see Ref. 10)

3.3 Varistor Suppression

Another type of transient suppression device is that of the voltage dependent resistor (varistor) in conjunction with the capacitor. The potential across a varistor is given by

$$V = DI^{\beta}$$

where

V is the voltage
I = the current
D = a constant between 10 and 10^4
β = an exponent usually between .17 and .35

Proost and Servranckx[12,13] have solved the non-linear equation for the circuit shown in Figure 11 using digital computers and have drawn nomographs for finding the peak value of the voltage V for a given solenoid, capacitor and varistor. A typical family of curves which shows the effect of the variation of some of the parameters of the varistor for a given solenoid is shown in Figure 12.

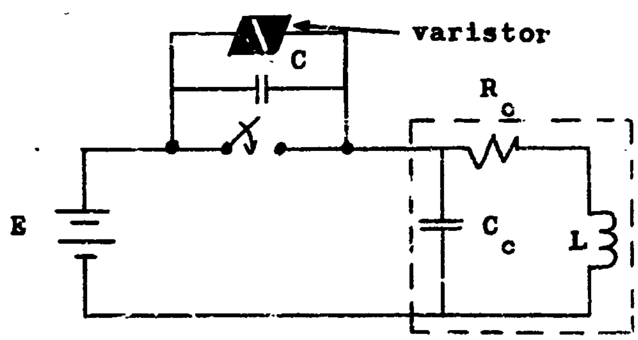


Figure 11. Varistor Suppression Circuit Across the Switch

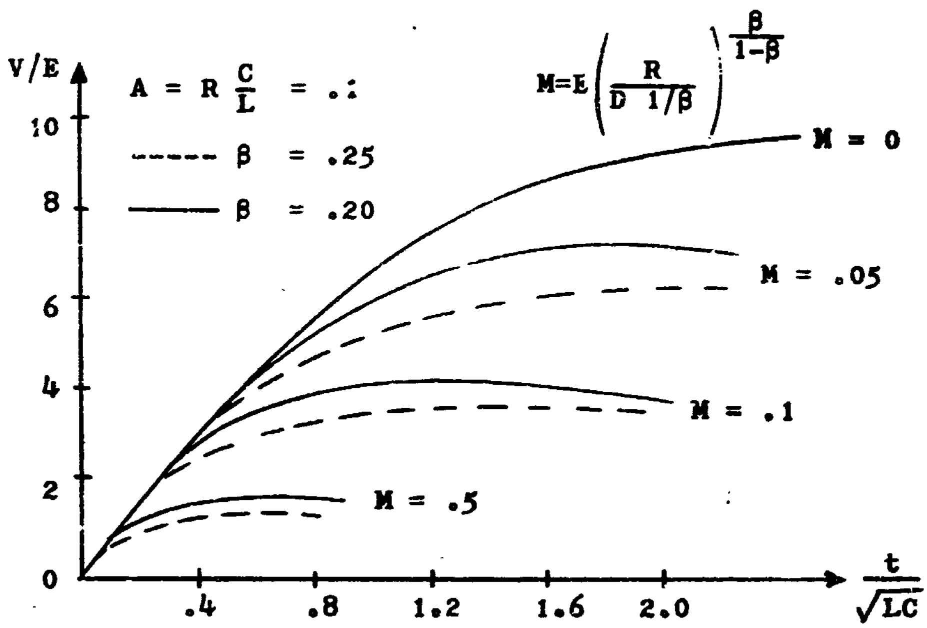


Figure 12. Typical Response Curves for Varistor-Capacitor Suppression Circuits (see Ref. 13)

Proost and Servranckx show that the capacitance should be chosen so that

$$C \geq \frac{25.4 \times 10^{-6}}{L} \mu \text{ fds.}$$

in order to reduce the peak voltage below the arcing potential.

For values of M greater than .1, the potential ratio V/E is practically independent of A, and the maximum value of V/E may be found from the graph given in Figure 13.

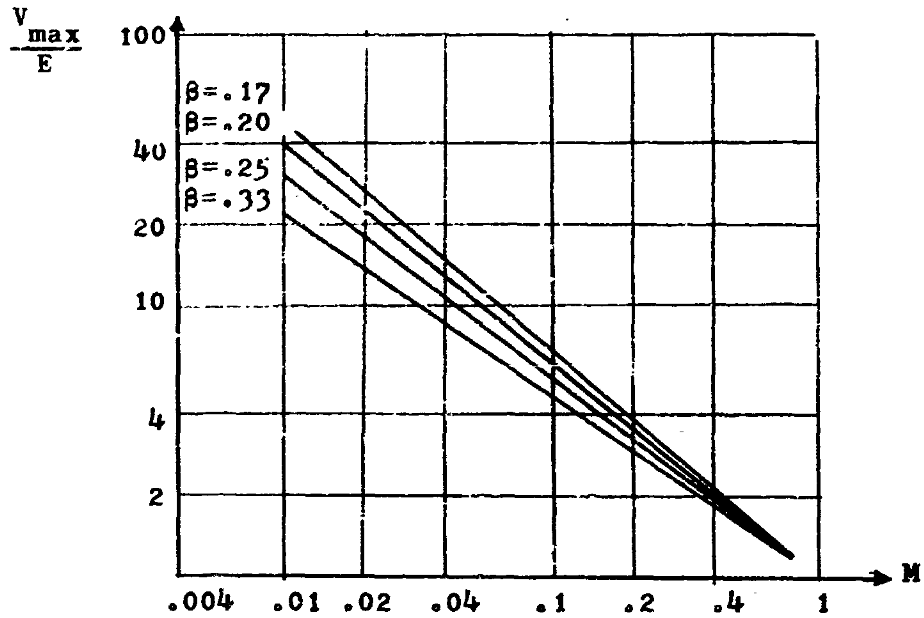


Figure 13. Graph of Maximum Induced Voltage for Various Values of β (see Ref. 12)

Thus, in order to apply suppression to a solenoid whose resistance is 28 ohms to a peak voltage under 100 volts for a 28 volt system, one must use a varistor with $\beta=.33$, $D=93$ or $\beta=.17$, $D=98$. To suppress this voltage below 50 volts, it will require the use of a varistor whose properties are $\beta=.33$, $D=41$ or $\beta=.17$, $D=43$. It is readily seen that in order to maintain low voltage transients, very low values of D are needed.

This type of suppression circuit has some drawbacks since there will be large currents upon closure of the contacts and some current drain when the switch is open.

3.4 Diode Suppression

Several references[7,8,14,15] consider diode arc-suppression and the use of diodes in suppression networks. The single diode placed in shunt with the inductor appears to be the most commonly used diode technique. This is shown in Figure 14.

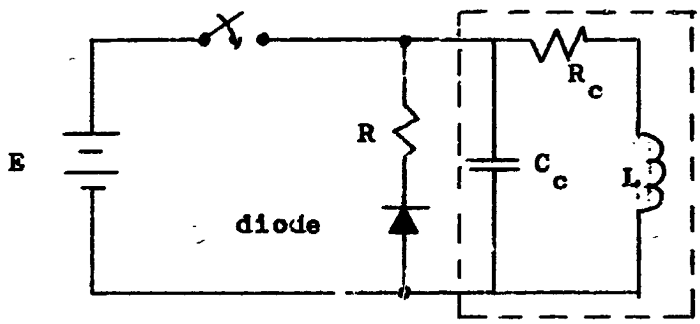


Figure 14. Single Diode Suppression (see Ref. 7)

The diode oriented as shown, is reverse biased when the switch is closed. The current, therefore, flows only through the branch containing the inductor.

When the switch is opened, the steady state current through the inductor forward biases the diode. This forms a current loop in which the energy stored in L is dissipated by R and R_c.

Another popular technique involves the use of two diodes placed back to back in shunt with the inductor as shown in Figure 15. Zener diodes are particularly well suited for this application since they possess a sharp voltage limiting characteristic in the reverse bias direction. A typical curve of a zerer diode current-voltage characteristics is shown in Figure 16.

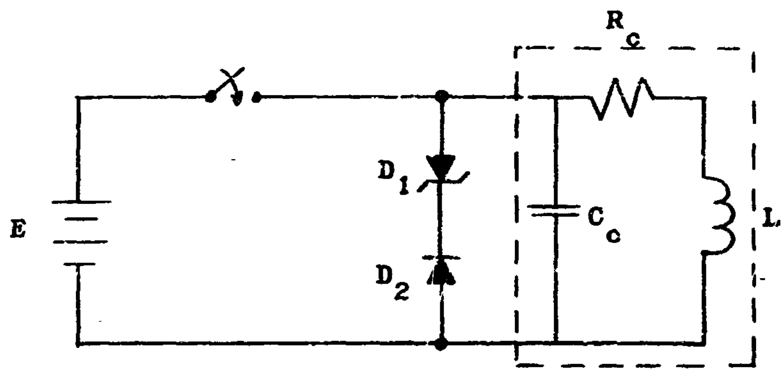


Figure 15. Suppression Circuit With One Zener Diode and One General Purpose Diode (see Ref. 14)

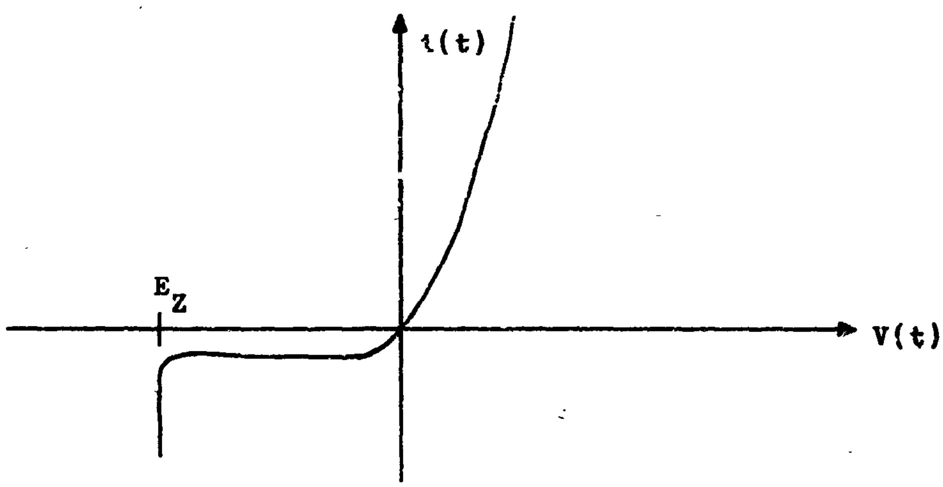


Figure 16. Typical Zener Diode Current-Voltage Curve

Referring to Figure 15, when the switch is closed, diode D_2 is reversed biased and blocks the flow of current through that branch permitting normal operation of the solenoid. For the supply voltage polarity shown, D_2 can be a general purpose type diode.

However, when the switch is opened, the continuous flow of current due to the collapsing magnetic field forward biases D_2 and reverse biases D_1. As a result, the voltage across the inductor is limited by the zener voltage of D_1. Through the proper selection of diodes, the peak transient voltages can be reduced using these techniques.

Budzilovich[8] points out that a diode may be used in an RC suppression network to minimize the voltage across the contacts upon opening, without affecting the current suppressing qualities of the RC network as the switch closes. This circuit is shown in Figure 17.

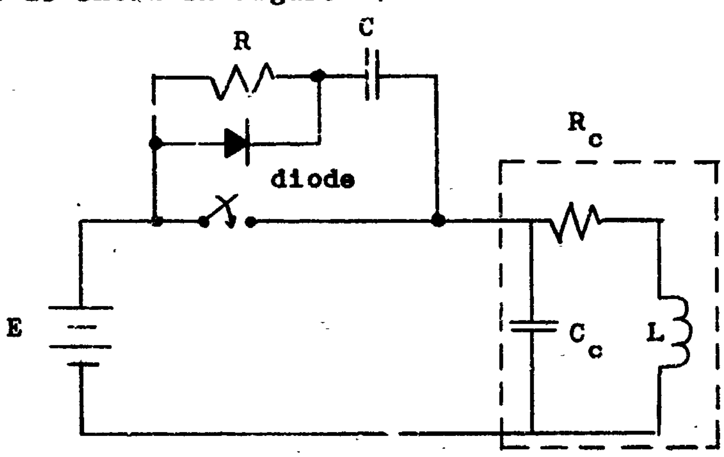


Figure 17. Improved RC Suppression Using Diode (see Ref. 8)

R_f = forward bias resistance of diode

R = current limiting resistor

C = capacitor

It was previously noted during the discussion of RC suppression that the voltage across opening contacts is minimized if the charging time constant of the capacitor is very small. This requires that R be small. On the other hand, R should be large to limit the current through the contacts of the closing switch. The diode serves to satisfy both of these conditions, first, by providing a low resistance path for charging in the forward bias direction and, second, by essentially blocking the current, when reverse biased, permitting C to discharge through R.

Thus, without the diode, the charging and discharging time constants of the capacitor are

$$\text{charge time} = \tau_c = RC$$
$$\text{discharge time} = \tau_d = RC$$

and with the diode

$$\tau_c = R_f C \ll RC$$

$$\tau_d = RC$$

the latter of which is recognized to be more desirable.

CHAPTER IV

EVALUATION OF THE EFFECTS OF SUPPRESSION CIRCUITS ON RELAY OPERATION

The use of suppression techniques to limit the arcing and transients in a circuit may cause secondary effects which must be investigated. Of considerable importance, is the effect of the suppression circuit on the operating time of a solenoid. De Ladio[7] has studied the changes brought about in the release time of certain relays due to the following types of suppression circuits: (1) capacitance shunts (2) zener diode semiconductor shunts (3) diode-resistance shunts and (4) varistor shunts.

Various values of shunting capacitors were used across a standard sealed relay (see Figure 18).

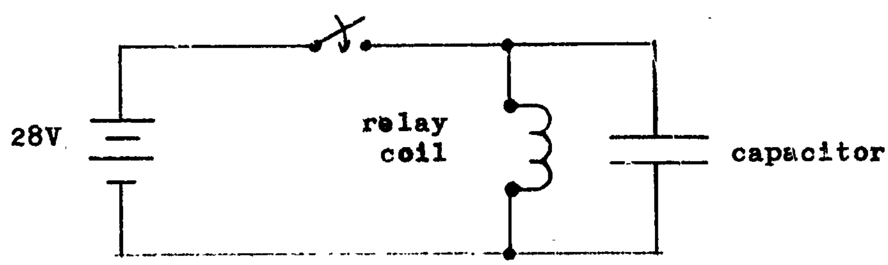


Figure 18 Capacitance Suppression Circuit

Effects of the peak induced voltage and the release time are shown in Figure 19.

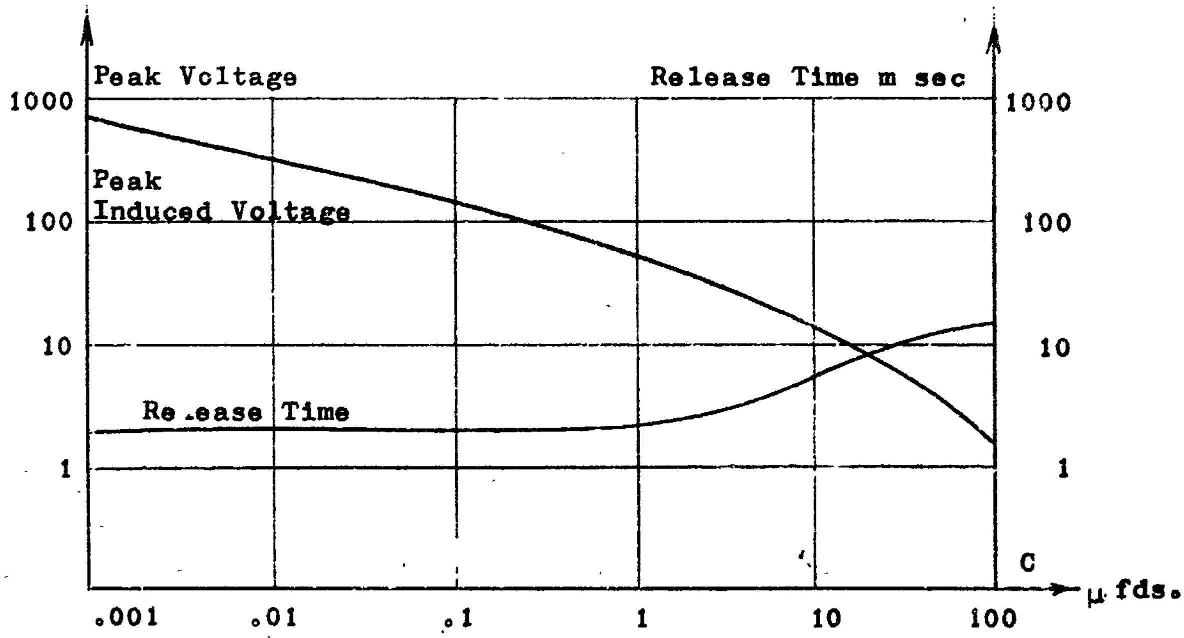


Figure 19. Effect of Shunt Capacitance on Relay Operation (see Ref. 7)

From the above graph it can be seen that the increase in capacitance does not affect the release time up to a certain point while continuously decreasing the peak induced voltage. Therefore, a capacitor may be very useful in circuits where release time is critical, and only a limited peak decrease is needed. The insertion of a small resistor in series with the capacitor to prevent current surge on closure does not change the shape of these curves appreciably.

In similar tests, two silicon diodes were used which had a Zener voltage of 60 and were placed cathode to cathode across the relay as shown in Figure 20. The results of the 60 volt

Zeners are shown in tabular form in Figure 20 at the end of this section. It was found that higher Zener voltages permit

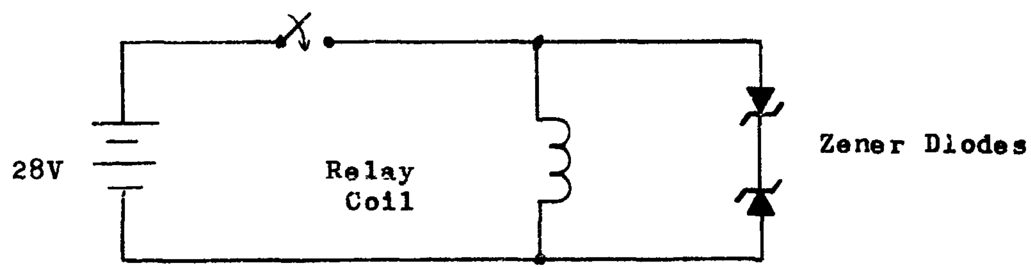


Figure 20. Zener Suppression Circuit

a higher peak with little effect on the release time, and too low a Zener voltage permits the diodes to conduct for a longer period which extends the release time.

The use of regular diodes in series with resistors has been studied for circuits as shown in Figure 21.

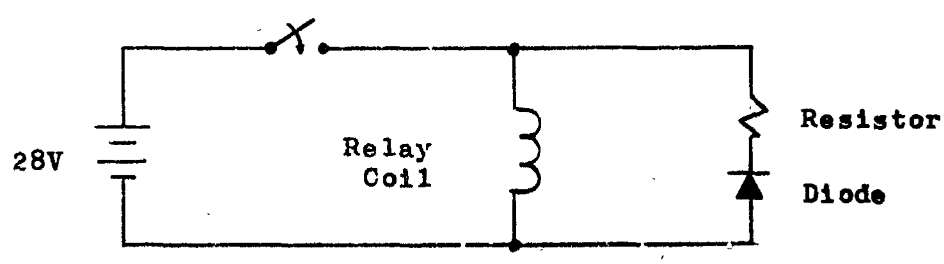


Figure 21. Diode-resistor Suppression Circuit

The resultant release times and peak induced voltage are shown as a function of the resistance R in Figure 22.

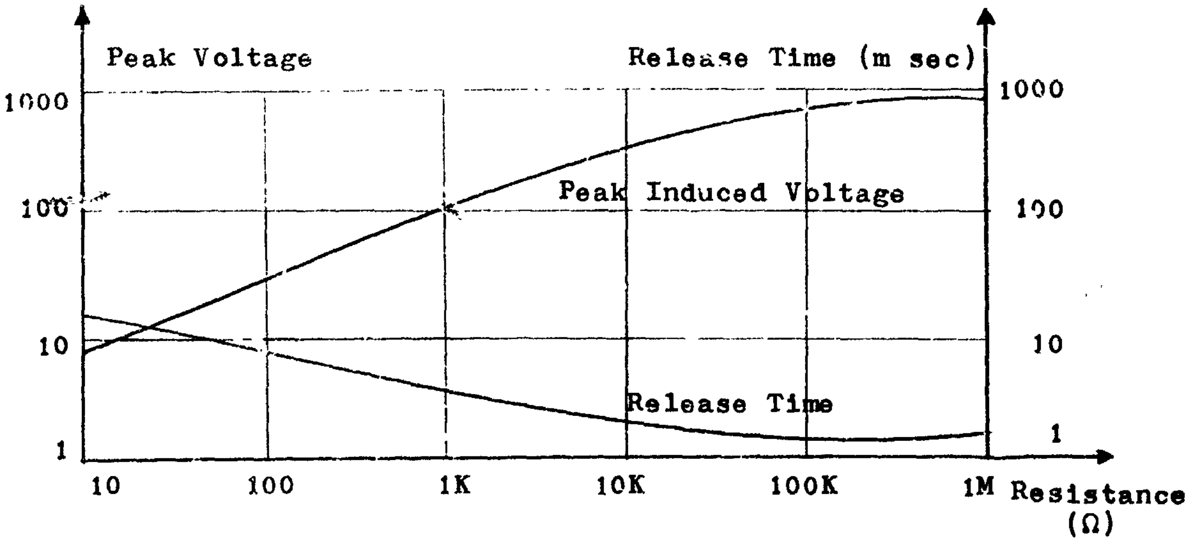


Figure 22. Effect of Resistance on Peak Voltage and Release Time (see Ref. 7)

It was found that varistors act similarly to the cathode to cathode Zener diodes but do not have as sharp a cutoff potential. An example of the circuit tested is shown in Figure 23 and the results on performance in Figure 24.

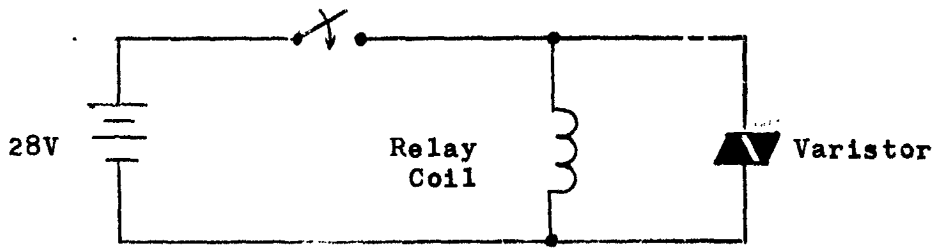


Figure 23. Varistor Suppression Circuit

Suppression type	28-Volt Hermatically Sealed Relay: Peak Voltage W/O	W	Release Time (m sec) W/O	W	28-Volt Crystal Case Relay: Peak Voltage W/O	W	Release Time (m sec) W/O	W
Capacitor (.22 fd)	950	120	1.5	1.55	580	28	2.1	2.2
Zener diodes (60 V)	950	190	1.5	1.70	580	170	2.1	2.3
Diode & 470 Resistor	950	80	1.5	5.4	580	20	2.1	5.1
Varistor (Globar 432BNR-35)	950	64	1.5	2.7	580	36	2.1	2.5

Figure 24. Comparison of Relay Performance Using Typical Suppression Techniques (see Ref. 7)

The table in Figure 24 illustrates that the type of suppression technique must be dependent upon the peak induced ltage reduction desired and also upon the tolerances with respect to the release time.

In general, if the release time is no problem then the use of diodes and resistors may be used to suppress the peak induced voltage to almost any tolerance level. On the other hand, the best compromise between induced voltage and release time is accomplished by varistor suppression. Thus, it appears that further attention must be given to the study of the use of varistors in particular and other types in general as well as the combination of two or more of these techniques.

CHAPTER V

COMMENTS

The above is a summary of pertinent information found in the survey of the literature listed in the bibliography. The purpose of the survey has been to determine the state of the art in suppressing the electrical noise generated by the switching of inductive circuits. In particular, it was desired to determine methods of noise suppression that have been devised and to establish models of both the unprotected inductive load and suppression circuits. These models consist of equivalent circuits, mathematical expressions and any other means of describing the phenomena that occur, and will be analyzed theoretically in Phase II to establish optimum noise suppression techniques.

In addition to the information found on noise suppression techniques, articles concerning the phenomena of arcing, the reduction of contact erosion through arc-suppression and the mechanics of relay operation were reviewed and are listed. It is anticipated that these will be useful in the analysis of the problem.

Some of the literature requested by mail has not been received. Upon arrival, it will be surveyed for pertinent facts relative to this study.

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